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Optimal Design Study of High Efficiency Indium Phosphide Space Solar Cells

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OPTIMAL DESIGN STUDY OF HIGH EFFICIENCY INDIUM PHOSPHIDE SPACE SOLAR CELLS

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Summary

Recently indium phosphide solar cells have achieved beginning of life AM0 efficiencies in excess of 19 percent at 25 °C. The high efficiency prospects along with superb radiation tolerance make indium phosphide a leading material for space power requirements. To achieve cost-effectiveness, practical cell efficiencies have to be raised to near theoretical limits and thin film indium phosphide cells need to be developed. Present work describes the optimal design study of high efficiency indium phosphide solar cells for space power applications using the PC-1D computer program. It is shown that cells with efficiencies over 22 percent AM0 at 25 °C could be fabricated by achieving proper material and process parameters. It is observed that further improvements in cell material and process parameters could lead to experimental cell efficiencies near theoretical limits. The effect of various emitter and base parameters on cell performance has been studied.

Introduction

Recently 4 cm^2 n^+pp^+ homoepitaxial indium phosphide solar cells grown by MOCVD have achieved beginning of life AM0 efficiencies in excess of 19 percent at AM0 (ref. 1). This is the highest efficiency reported for InP cells to date for cells measured at NASA Lewis Research Center. Based on the assumptions that all the incident photons with energies greater than or equal to the bandgap energy generate free carriers and that their recombination is entirely radiative, an upper limit for conversion efficiency of 29 percent for a semiconductor with bandgap of 1.30 eV has been obtained (ref. 2). The indium phosphide bandgap (1.35 eV) is quite close to the bandgap (1.30 eV) considered in the maximum conversion efficiency calculations (ref. 2). The high efficiency prospects along with superb radiation tolerance (refs. 3 and 4) make indium phosphide a leading material for space power requirements. To achieve wide spread use, however, practical cell efficiencies have to be raised to near theoretical limits while maintaining high radiation resistance and cells utilizing thin layers of indium phosphide only for active regions need to be developed. Current heteroepitaxial indium phosphide cells on gallium arsenide or silicon substrates have low efficiencies (ref. 5) due to large numbers of dislocations and their effect on cell performance has been described elsewhere (ref. 6).

The present paper describes an optimum design study of high efficiency indium phosphide solar cells for space power applications using the PC-1D computer program (ref. 7). It is shown that cells with efficiencies over 22 percent AM0 at 25 °C could be fabricated by achieving proper material and process parameters. It is observed that further improvement in cell material and process parameters could lead to experimental cell efficiencies near theoretical limits. The effects of various emitter and base parameters (minority carrier diffusion lengths, thickness, grid shading, cell series resistance, front/back surface recombination velocities, etc.) on cell AM0 efficiency have been studied.

Design Approach

The PC-1D is a one-dimensional computer program for investigating semiconductor devices. The program accurately solves the device transport equations based on the isolated-

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element approach. A number of researchers have used the PC-1D for analyzing various semiconductor device problems as well as for solar cell modeling.

Based on a set of optimally designed cell material and process parameters, the current-voltage characteristics of the indium phosphide solar cell are calculated. The cell performance parameters are extracted from these calculations. The effect of various emitter and base parameters on cell efficiency is studied by varying the parameter of interest and keeping other parameters constant.

In the case of indium phosphide, the exact value of the intrinsic carrier concentration is still in question. In this work we have used the average value (8×10^6 cm^{-3}) of the intrinsic carrier concentration as suggested in reference 8.

Results and Discussion

Figure 1 shows the calculated current-voltage characteristics of an optimally designed n^+p indium phosphide solar cell for the parameters given in Table 1. This design yields with the cell open circuit voltage of 922 mV, short circuit current density over 40 mA/cm^2, fill factor of 0.84 and AM0 efficiency in excess of 22 percent at 25 °C. This design study shows what must be done to achieve improvement in cell efficiency over current state-of-the-art indium phosphide cells. Some of the cell material and process parameters of Table I have already been achieved and other parameters, especially the minority carrier diffusion lengths and surface recombination velocities must be realized to obtain high efficiency cells.

In figures 2 and 3 the effects of emitter minority carrier (hole) diffusion length and base minority carrier (electron) diffusion length respectively on cell efficiency have been studied. The efficiency initially improves rapidly and afterwards saturates with increasing minority carrier diffusion lengths. The hole diffusion length affects the cell current only, while the electron diffusion length affects both the cell current as well as the voltage. The results shown in figures 2 and 3 emphasize the requirement of long diffusion lengths for obtaining high efficiencies.

Figure 4 plots the variation of cell efficiency with emitter thickness from 10 to 100 nm. From these results it is clear that cell efficiency improves significantly with the decrease in emitter thickness. This is due to reduced recombination, which improves the current, while the voltage remains almost unchanged with the reduction in emitter thickness. Fabrication of thin emitters free from other process interactions is a challenge in itself, but emitters around 20 nm should be targeted for better results.

In figure 5 we have demonstrated the influence of front contact grid shading on cell efficiency. A reduction in grid shading increases cell current, which has a net effect on the cell efficiency. However the grid coverage has to be optimized considering its series resistance, cell contact fabrication technique used and the cell application (flat plate/concentrator). In the optimal design study 5 percent grid coverage has been considered. It has been possible to effectively reduce the grid shading losses by the use of prismatic covers on cells (ref. 9).

In figure 6 we have studied the effect of cell series resistance on cell efficiency. The series resistance of a solar cell has to be reduced to its lowest possible value to keep the power losses at a minimum. A full discussion of the problem is beyond the scope of the present paper. In the design study we have considered 0.5 $\Omega\text{-cm}^2$ as the cell series resistance. A lower value would improve efficiencies still further.

Figures 7 and 8 show the effect of front and back surface recombination velocities on cell efficiency respectively. Lower values of SRV's would help in achieving high cell efficiencies. Due to the absence of passivation layers, present indium phosphide cells have high front SRV's. Therefore proper passivating layers need to be developed. The back SRV's could probably be lowered by suitable BSF and BSR layers and require to be further investigated. Calculations have shown that the front SRV affects the cell current only, while the back SRV affects the voltage as well as the current. This is contrary to the results found in cells with poor emitter quality where the front SRV has no effect of efficiency (ref. 10).

From the results described in figures 2 to 8, it is clear that further increase in cell efficiencies up to 25 percent AM0 could be achieved by improvements in cell material and process parameters.

Conclusions

An optimal design study of indium phosphide solar cells has shown that cell efficiencies in excess of 22 percent AM0 at 25 °C are possible. The effect of various emitter and base parameters on cell efficiency has been studied. Further improvements in cell material and process parameters could lead to experimental cell efficiencies near theoretical limits.

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Table I. Parameters of an Optimally Designed InP Solar Cell

Emitter thickness, nm	20
Emitter doping, cm^{-3}	$2x10^{18}$
Hole diffusion length, μm	0.1
Front surface recomb. velocity, cm/sec	10^4
Front grid coverage, percent	5
Cell series resistance, Ω-cm^2	0.5
Base thickness, μm	5
Base doping, cm^{-3}	$5x10^{16}$
Electron diffusion length, μm	20
Back surface recomb. velocity, cm/sec	10^5

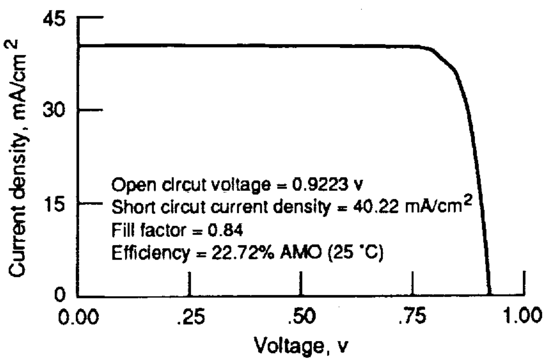

Figure 1.—Calculated I-V characteristics of an optimally designed $n^{+}p$ Indium Phosphide solar cell.

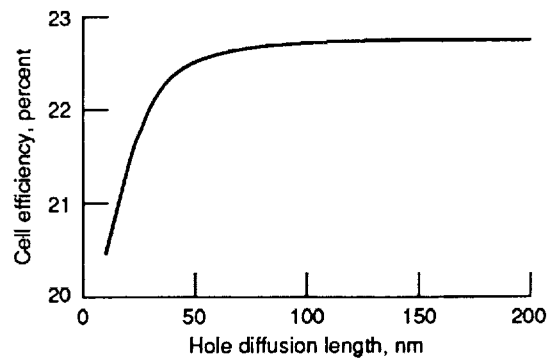

Figure 2.—Effect of emitter minority carrier (hole) diffusion length on cell efficiency.

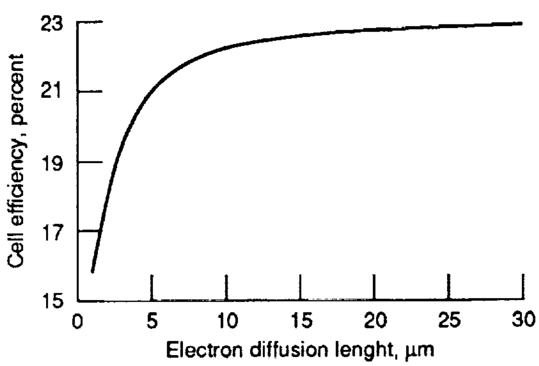

Figure 3.—Effect of base minority carrier (electron) diffusion length on cell efficiency.

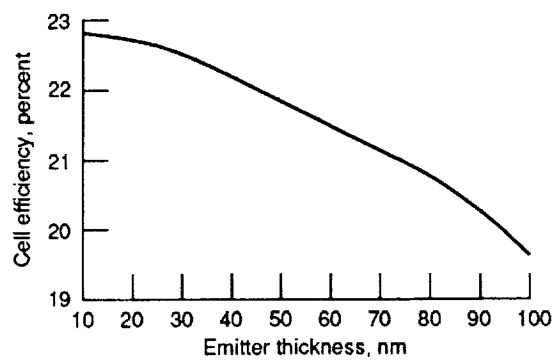

Figure 4.—Effect of emitter thickness on cell efficiency.

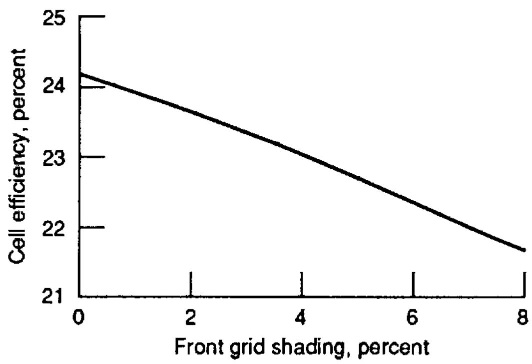

Figure 5.—Effect of front contact grid shading on cell efficiency.

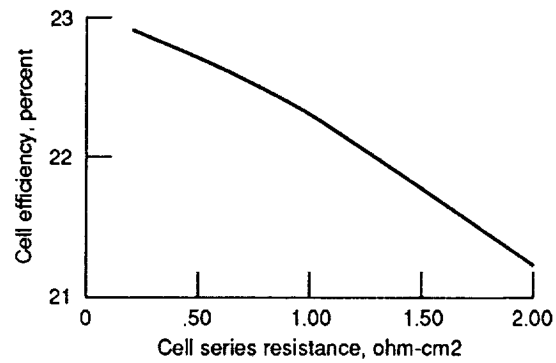

Figure 6.—Effect of cell series resistance on cell efficiency.

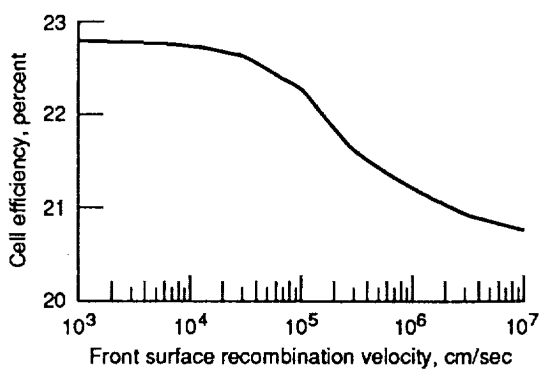

Figure 7.—Effect of front surface recombination velocity on cell efficiency.

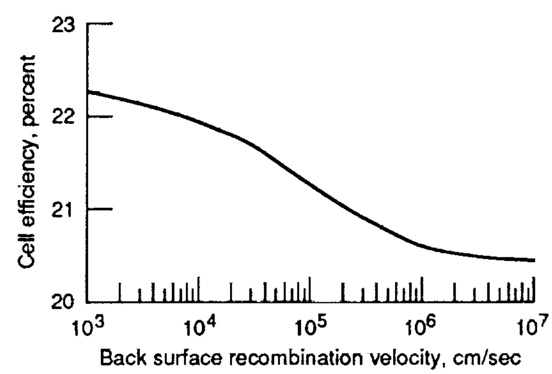

Figure 8.—Effect of back surface recombination velocity on cell efficiency.

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16. Abstract
Recently indium phosphide solar cells have achieved beginning of life AM0 efficiencies in excess of 19 percent at 25 °C. The high efficiency prospects along with superb radiation tolerance make indium phosphide a leading material for space power requirements. To achieve cost-effectiveness, practical cell efficiencies have to be raised to near theoretical limits and thin film indium phosphide cells need to be developed. Present work describes the optimal design study of high efficiency indium phosphide solar cells for space power applications using the PC-1D computer program. It is shown that cells with efficiencies over 22 percent AM0 at 25 °C could be fabricated by achieving proper material and process parameters. It is observed that further improvements in cell material and process parameters could lead to experimental cell efficiencies near theoretical limits. The effect of various emitter and base parameters on cell performance has been studied.

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